The Lunar Space Communications Architecture From The KARI-NASA Joint Study*

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During October 2014 – April 2015, Korea Aerospace Research Institute (KARI) and the National Aeronautics and Space Administration (NASA) conducted a feasibility study for the purpose of identifying potential areas of cooperation in lunar robotic exploration activities. A key objective of the joint study was to define a space communications architecture that will serve as a framework for accommodating the communications and navigation capabilities and services provided by NASA's Deep Space Network (DSN), the Korea DSN (KDSN), a potential lunar relay, the Korea Pathfinder Lunar Orbiter (KPLO), and the KPLO mission operations system (MOS). This lunar communications architecture is intended to support, in addition to the KPLO mission (to be launched in 2018), other lunar potential missions, i.e., NASA or KARI lunar CubeSat missions and a NASA Resource Prospector mission, to be operational in the 2018-2021 time frame. A salient feature of this architecture is the service paradigm propagated from that of the DSN. Both DSN and KDSN will operate on a multi-mission basis, serving multiple flight missions concurrently. They execute a set of standard services through Consultative Committee on Space Data Standards (CCSDS)-compliant standard protocols to communicate with the spacecraft of the user missions over the space-ground communications link, and CCSDS-compliant standard interfaces with the MOS over the ground-to-ground link. In other words, they are interoperable to each other and, from the viewpoint of the user missions of KARI and NASA; they can obtain "cross support" by the network assets of the two agencies. The second feature of the lunar space communications architecture is the existence of a prototypical Lunar Network, enabled by the lunar relay asset. This is a new type of communications asset in the lunar region. Three different relay configurations, i.e., the integrated relay payload, the hosted relay payload, and the independent relay satellite, were assessed for their feasibility, functionality, and performance. Another feature is the multiplicity of the communications links, i.e., trunk link, in-situ link, and Direct To/From Earth (DTE/DFE) links, and their associated complexity due to the diversity of user missions, e.g., multiple frequency bands (X-, S-, and UHF-bands) to be supported by the radios in the system architecture.

Based on and extended from the architecture established by the KARI-NASA collaborative effort for the 2018-2021 timeframe, the more powerful, encompassing international space communications architecture for lunar exploration in the 2020s is defined. In view of the potential abundance of lunar spacecraft to be launched during the 2016-2025 timeframe and the fact that there exists no common communications architecture to guide these missions yet, a decadal space communications architecture may benefit many future missions from several space agencies. New capabilities introduced into the architecture are Ka and optical links for high-rate data return, dedicated lunar relay satellites, space internetworking using Disruption Tolerant Networking (DTN), higher level standard services (e.g., file level), uplink multiplexing/encoding, and the service management capabilities based on CCSDS standards. Their ramifications to network operations and missions operations are also assessed.

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The paper addresses the lunar communications architectures for two time frames: the 2018-2021 timeframe (covering the KARI-NASA study) and the 2016-2025 era.[4]

I. Purpose of The Paper

THIS paper covers the lunar space communications architecture defined by the feasibility study jointly conducted by the KARI and NASA during October 2014 – April 2015. From the KARI perspective, a formalized space communications architecture, while crucial to its first lunar mission, the Korea Pathfinder Lunar Orbiter (KPLO), has many long-term ramifications to the entire lunar exploration program that the KARI will undertake during the next decade. To NASA, in spite of its multitude of lunar missions, past and present, taking another new, fresh look at the architecture with a newcomer, who can bring new ideas and concept, is a precious opportunity to address some important issues for the future lunar exploration.

The paper, therefore, covers the lunar communications architectures for the 2018-2021 timeframe and, beyond that, the 2016-2025 era.

II. Introduction of the Joint KARI-NASA Study

In accordance with a KARI-NASA inter-agency Agreement[1], NASA and KARI conducted a feasibility study for the purpose of identifying potential areas of cooperation in lunar robotic exploration activities. Two working groups were formed under the Agreement to identify potential areas of collaboration. The Space Communications Working Group studied joint communications and navigation activities, services, and experiments, including NASA's Deep Space Network (DSN), the Near Earth Network (NEN), the Korea DSN (KDSN), and other mission operations support, DTN, and the feasibility of KARI hosting a NASA-provided communications relay on the KPLO. The Spacecraft Systems Working Group studied technologies and subsystems needed for lunar orbiters, landers, and rovers including the spacecraft bus accommodations for a communications relay payload.

It was expected that the cooperation on space communications and spacecraft systems technologies would enable more affordable and capable lunar exploration missions for both KARI and NASA. This feasibility study represented an important first step toward the potential collaborative effort.

In the near term, there are some lunar missions that were of particular interest for the feasibility study. South Korea's Lunar Exploration Program (KLEP) will launch KPLO on a non-Korean launch vehicle in 2018. NASA is studying a Resource Prospector (RP) mission to search for ice and other volatiles in the polar regions of the Moon in 2020. In addition, both agencies have some candidate science instruments as the KPLO payload and some lunar CubeSat/SmallSat missions to be launched as secondary payloads on the Expendable Launch Vehicle for NASA's Exploration Mission 1 (EM-1) and KARI's KPLO, respectively, during the 2018–2021 time frame. The feasibility study provided some insights into those areas where mutual benefits to these missions could be gained.

III. Lunar Missions of the Next 10 Years – KARI, NASA and Other Space Agencies

During the next decade, there will be many missions to be launched for lunar exploration (see Table 1). Different from the mission set of 2005-2015, we see a significant increase of landed vehicles, some sample return missions, the start of a robotic lunar base, and the use of CubeSat/SmallSat for technology demonstration and science investigation. However, since each agency tends to focus its investment on the immediate means needed to achieve certain specific mission objectives, little or no attention has been given to the infrastructure, e.g., space communications capabilities, for the long-term exploration. The space communications architecture, as described in Section IV, defined by the KARI-NASA joint study reflects an attempt to address that issue, although in a very limited scope due to its bi-lateral nature.

Table 1. Lunar Missions To Be Launched in 2015-2025 Era

Mission	Launch Year	Agency	# of Vehicles	Mission Type
Chandrayaan-2	2018	ISRO	3	Orbiter/lander/rover
Chang'e 4	2018	CNSA	2	Lander/rover
Chang'e 5	2017	CNSA	2	Orbiter/rover for sample return
Chang'e 6	2020	CNSA	2	Orbiter/rover for sample return
KPLO	2018	KARI	1	Orbiter
Korean Lunar Mission	2021	KARI	3	Orbiter/lander/rover
Luna 25	2024	RFSA	1	Lander

Luna 27	2020	RFSA	1	Rover
Luna 26	2020	RFSA	1	Orbiter
SLIM	2019	JAXA	1	Lander
SELENE-2*	2022	JAXA	3	Orbiter/lander/rover
Resource Prospector*	2020	NASA	2	Lander/rover
EM-1**	2018	NASA	1	Orbiter
EM-2**	2020	NASA	1	Orbiter
Lunar Flashlight*	2018	NASA	1	CubeSat Orbiter
Lunar IceCube	2018	NASA	1	CubeSat Orbiter
Lunar H-Mapper	2018	NASA	1	CubeSat Orbiter
ArgoMoon	2018	ASI	1	CubeSat Orbiter
SLSSLIM	2018	JAXA	1	CubeSat Lander
EQULLEUS	2018	JAXA	1	CubeSat Orbiter

* Not yet an approved mission

** Strictly not exactly a lunar mission; rendezvous to the Distant Retrograde Obit (DRO)

IV. Description of Lunar Space Communications Architecture – From the Joint Study

This section summarizes the end-to-end lunar space communications architecture from the KARI-NASA joint study. The full results are contained in the final report[2].

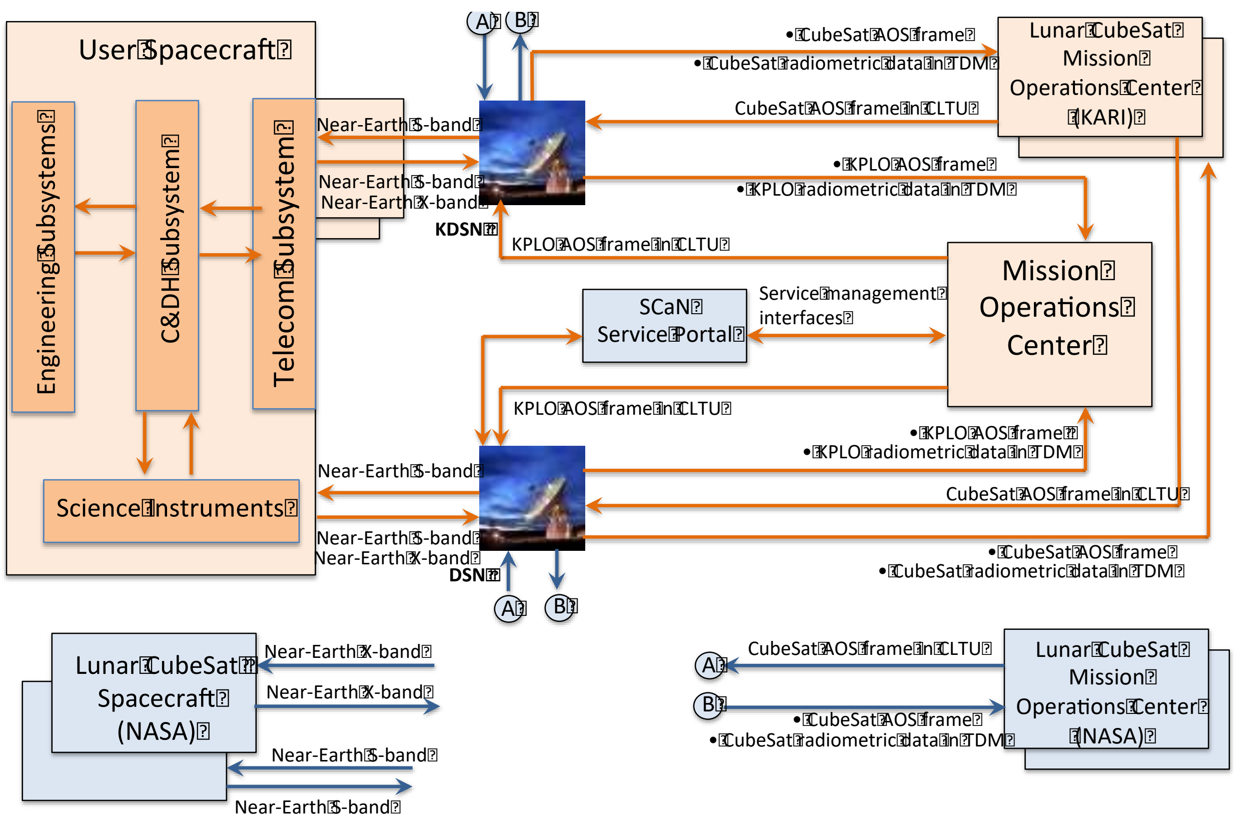


Figure 1. Proposed Lunar Space Communications Mission Architecture [without relay]

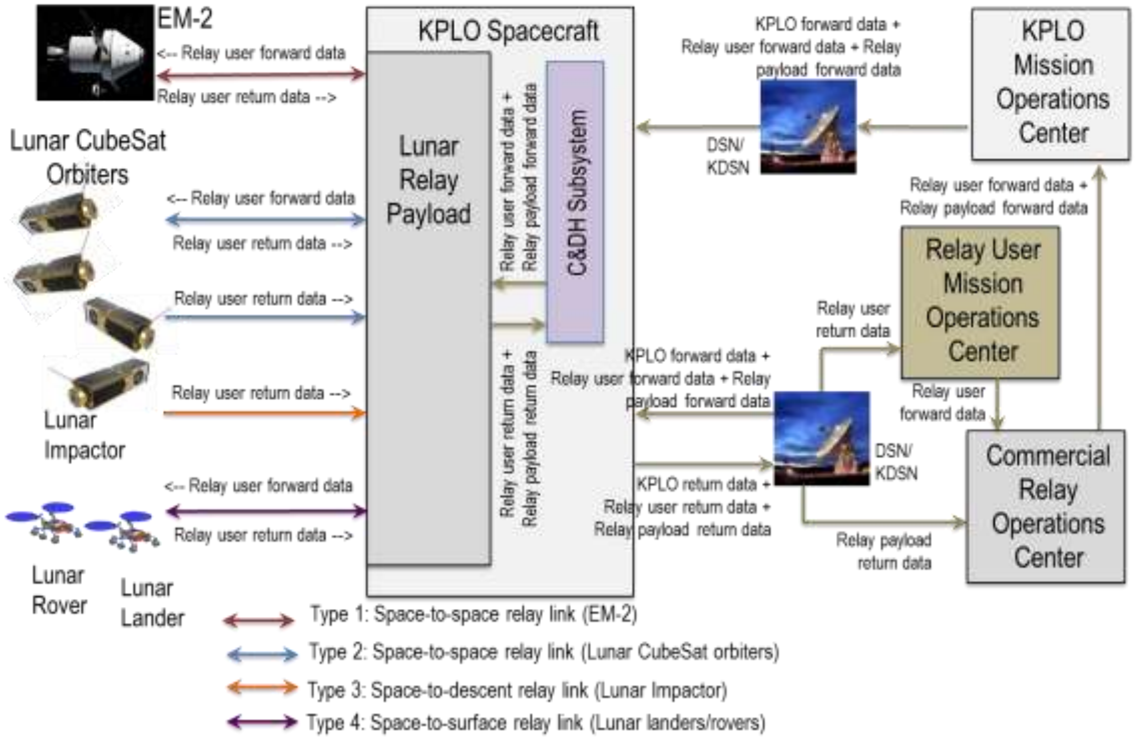


Figure 2. Proposed Lunar Space Communications Mission Architecture [with relay]

A. Key Characteristics of Lunar Space Communications Architecture

In Korea, to provide services to lunar missions during the 2018–2021 time frame, the current lunar space communications architecture is extended to incorporate the network assets of the KARI, i.e., the Korean DSN (KDSN) station, other stations, and the potential lunar relay. A key feature of this architecture is the service paradigm propagated from that of the DSN. Both DSN and KDSN will operate on a multiple mission basis, serving multiple flight missions concurrently. They execute a set of standard services through CCSDS-compliant standard protocols to communicate with the spacecraft of the user missions over the space-ground communications link, and CCSDS-compliant standard interfaces with the MOS over the ground-to-ground link. They can obtain "cross support" by the network assets of the two agencies. Figure1 illustrates the service paradigm feature of the lunar space communications architecture without relay, only using the KPLO. And Figure 2 illustrates the lunar space communication architecture with relay using the KPLO.

As described in Section IV.C, the envisioned commercial relay asset could exist in one of the three different configurations: 1) an integrated relay payload, the host relay payload (the option shown in Figure 2), 2) a hosted payload treating the relay capability as the hosted payload and KPLO as the host, and 3) an independent relay satellite co-manifested with KPLO for launch.

B. Description of Space Communications Services for KARI-NASA Cross Support

To KARI-NASA Cross Support, the lunar missions, regardless of KPLO, lunar CubeSat/SmallSat missions, or RP, will rely heavily on the space communications and tracking services provided by the network assets, to achieve their mission objectives and conduct their day-to-day mission operations. Central to the collaboration between the KARI and NASA in joint lunar exploration is the cross-support to the lunar missions of the two agencies by the network assets owned and operated by the two space agencies.

Relevant DSN assets for cross-support to the KPLO and other lunar missions are as follows:

- 34-m Beam Waveguide-1 (BWG-1) subnet: S-band uplink and downlink; X-band uplink and downlink
- Other 34-m BWG: X-band uplink and downlink
- 34-m high-efficiency (HEF) subnet: S-band downlink; X-band downlink only

Relevant DSN uplink/downlink frequencies, transmitting powers and receiving performance are as follows:

- S-band uplink: 2025–2110 MHz

    - 200 W ~ 20 KW transmitter at 34-m antenna
- S-band downlink: 2200–2290 MHz
    - G/T: 37 dB/K
- X-band uplink: 7190–7235 MHz
    - 200 W ~ 20 KW transmitter at 34-m BWG antenna
- X-band downlink: 8450–8500 MHz
    - G/T: 50 dB/K

Three basic types of services are available to the KPLO from the NASA DSN for cross-support with KARI DSN:

- Forward link data service (See Table 2 for key attributes of this service)
- Return link data service (See Table 3 for key attributes of this service)
- Radiometric data service (See Table 4 for key attributes of this service)

In addition, the DSN could provide the Forward File Service to the KPLO. This is a service that takes a CCSDS File Delivery Protocol (CFDP)-structured file received from the KPLO MOC using the CCSDS Generic File Transfer Protocol (scheduled to be defined by the CCSDS in 2015) and radiates it to the KPLO spacecraft via CFDP over the space link.

Also, the DSN could provide Return File Service to the KPLO. This is a service that takes a CFDP-structured file received from the KPLO spacecraft, via the CFDP over the space link, and delivers it using the CCSDS Generic File Transfer Protocol (scheduled to be defined by the CCSDS in 2015) to the KPLO MOC.

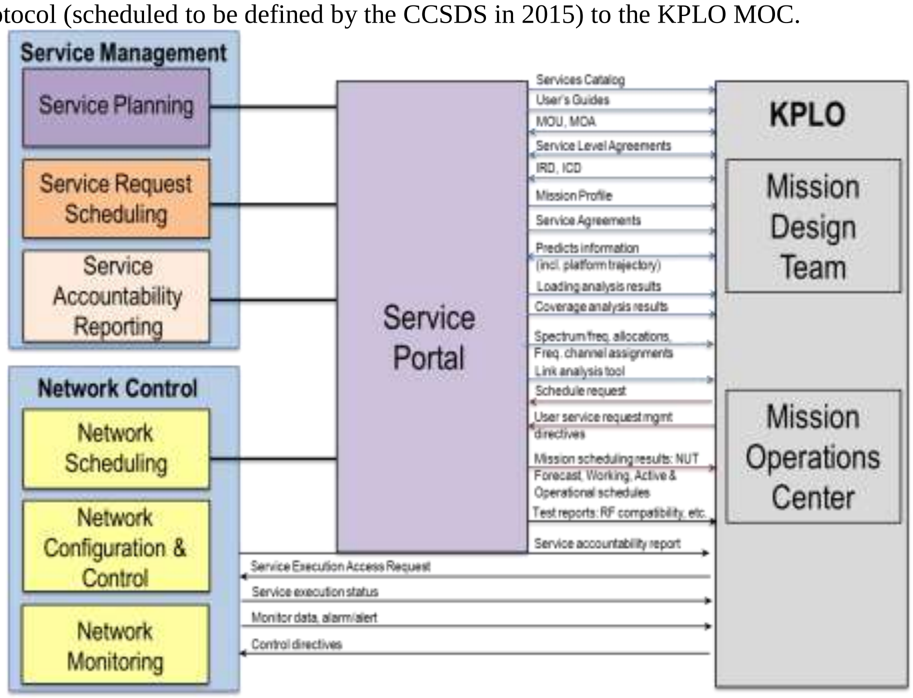


Figure 3. DSN–KPLO Interfaces for Service Management and Network Control Functions

To plan for and schedule the instances of above services, the DSN, with the cooperation of the KPLO, must conduct the service management functions, including service planning and service request scheduling. During the operational phase, the network control functions are performed to schedule network assets, configure equipment prior to service execution, control service execution, and monitor status and behavior during the contact periods. While most of the network control activities are internal to the DSN, some visibility and controllability are provided to the user missions. Figure 3 depicts the interfaces between KPLO and DSN for the service management and network control functions.

Table 2. DSN Forward-Link Data Service to KPLO - Key Attributes

Parameter	Value
Frequency bands	Near-Earth S-, X-band
Antenna types	34-m BWG, 34-m HEF
Polarizations	Right Circular Polarization (RCP) or Left Circular Polarization (LCP); No RCP/LCP simultaneity
Modulation types	BiPhase Shift Keying (BPSK) on subcarrier for uplink rate ≤4 kbps; BPSK directly on carrier for uplink rate 4 kbps to 256 kbps
Modulation formats	Non-Return to Zero (NRZ): Level (L), Mark (M), Space (S); Bi-phase L or Manchester, M, S
Carrier/Subcarrier waveform	Residual carrier: sine wave Subcarrier: 8 or 16 kHz
Uplink acquisition types	CCSDS Physical Link Operations Procedure-2 (PLOP-2)
Forward link data rate	Maximum 256 kbps Minimum 7.8 bps
Channel coding	None; expect at least Bose-Chaudhuri-Hocquenghem (BCH) code for error detection done by user missions per CCSDS Synchronization and Channel Coding (ref. CCSDS 131.0-B-2)
Data from MOC to DSN	Stream of Advanced Orbiting Systems (AOS) frames over a TCP/IP interface; CCSDS Space Link Extension (SLE) Enhanced Forward Communication Link Transfer Unit (CLTU) Service (ref. CCSDS 912.11-O-1 and ref. CCSDS 912.1-B-3)
Data from DSN to spacecraft	Encoded AOS frame per CCSDS AOS Space Data Link Protocol (ref. CCSDS 732.0-B-2)
Data unit size	Maximum CLTU size: 32,752 bits Minimum: 16 bits A series of CLTUs can be contiguously radiated

Table 3. DSN Return-Link Data Service to KPLO - Key Attributes

Parameter	Value
Frequency bands	Near-Earth S-, X-band
Antenna types	34-m BWG, 34-m HEF
Polarizations	RCP or LCP; RCP/LCP simultaneity at some stations
Modulation types	Phase Shift Keying (PSK) on residual carrier (with or without subcarrier) BPSK on suppressed carrier (no ranging) Quadrature PSK (QPSK), Offset Quadrature PSK (OQPSK) (no ranging)
Modulation formats	NRZ: L, M, S; Bi-phase L or Manchester, M, S
Carrier/Subcarrier waveform	Residual carrier: sine or square wave

Return link data rate	Maximum: 10 Mbps (10 Msps) or higher extensible Minimum: 10 bps (20 sps) (>40 bps recommended for timely acquisition)
Forward error correction code	Low Density Parity Checking (LDPC) rate 1/2 CCSDS Synchronization and Channel Coding (ref. CCSDS 131.0-B-2)
Data from DSN to MOC	Stream of AOS frames over a TCP/IP interface; CCSDS SLE Return All Frames/Return Channel Frames (RAF/RCF) (ref. CCSDS 911.1-B-3 and 911.2-B-2); online delivery mode only. Online and off-line delivery modes
Data from spacecraft to DSN	Encoded AOS frame per CCSDS AOS Space Data Link Protocol (ref. CCSDS 732.0-B-2)
Data unit size (information bits only)	Virtual Channel Data Unit (VCDU): 8920 bits (nominal), 1760 bits (safing and critical events), 16 kbits (maximum)

Table 4. DSN Radiometric Data Service to KPLO - Key Attributes

Parameter	Value
Frequency bands	Near-Earth S-, X-band uplink and downlink
Antenna types	34-m BWG, 34-m HEF
Tracking data types	Range, Doppler, Angle (mainly for initial acquisition during Launch and Early Orbit Period, LEOP)
Tracking mode	Coherent Noncoherent
Ranging type	Pseudo-noise code
Range accuracy (1σ error)	1 meter
Doppler accuracy (1σ error)	0.05 mm/s, 60-s compression
Doppler measurement rate	0.1 second
Downlink carrier level	Residual: 10 dB Loop Signal/Noise Ratio (SNR) minimum Suppressed: 17 dB Loop SNR minimum QPSK/OQPSK: 23 dB Loop SNR minimum
Range power level	+50 to -10 dB Hz (downlink ranging power to noise spectral density ratio, P_r/No)
Data latency	Doppler/Range: 5 minutes (95%)
Data modes (DSN to MOC)	Stream data mode File data mode
Delivery modes (DSN to MOC)	On-line; Off-line
Interface standards	CCSDS Tracking Data Messages (TDMs) for data contents/format (ref. CCSDS 503.0-B-1) over CCSDS Generic File Transfer Protocol [TBS]

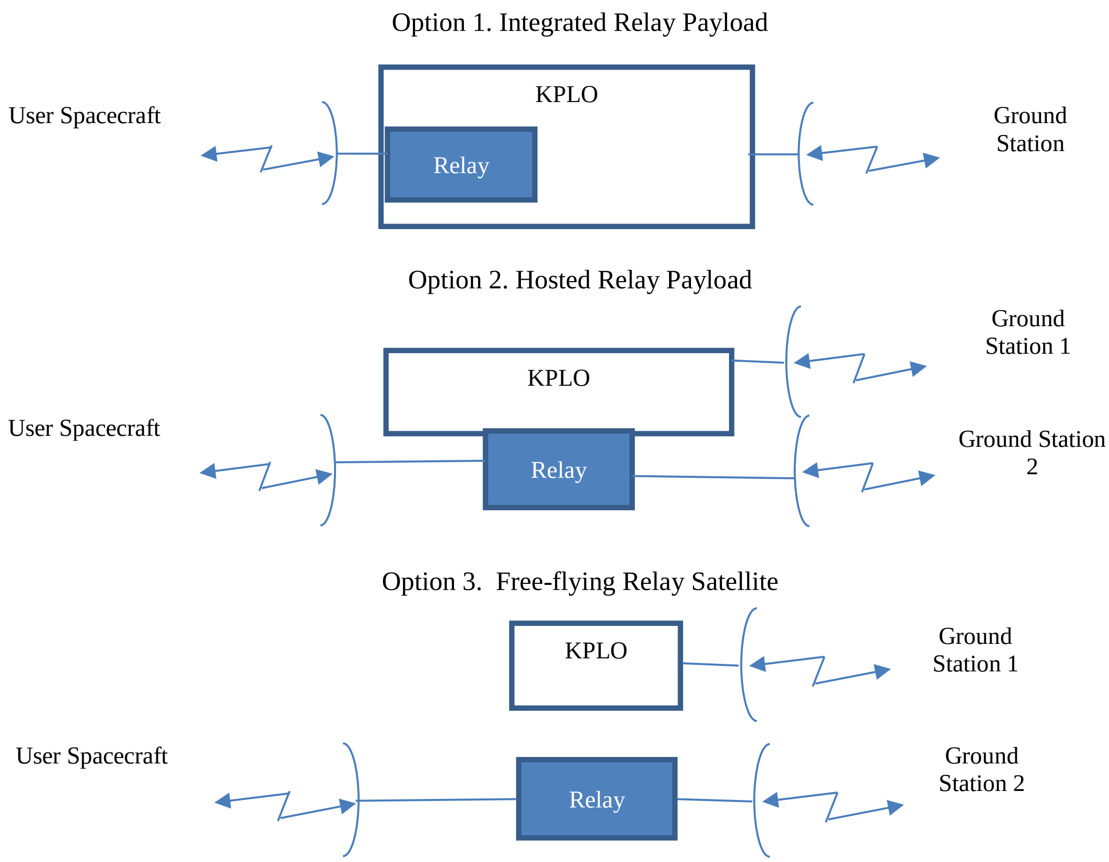
C. Lunar Relay Services

As shown in Figure 2, the space communications architecture includes a hypothetical relay capability. While the KPLO does not carry any relay payload in its baseline design and implementation, the KARI-NASA joint study considered it an important entity of the architecture in the long term, hence the case study using KPLO as the hosted spacecraft or conduit for a potential relay capability. A more involved, encompassing analysis of this subject has been conducted after the joint study. The results are covered in Section V.A.

Three types of relay were assessed. They are summarized in Table 5.

Table 5. Options of Lunar Relay Capability Related To A Science Orbiter

Option 1: Integrated Relay Payload	Option 2: Hosted Relay Payload	Option 3: Free-flying Relay Satellite
The relay payload communicates with user spacecraft via proximity link, but not with Earth stations via trunk link.	The relay payload communicates with user spacecraft via proximity link and with Earth stations via trunk link.	The relay satellite is a "passenger", co-manifested on the expendable launch vehicle (ELV) used by the science orbiter.
Relies on the resources as well as some devices of the hosting spacecraft.	More self-contained than Option 1. Still relies on some resources of the hosting spacecraft	Does not use or share any resources with the hosting spacecraft.



V. Lunar Space Communications Architecture – Beyond The KARI/NASA Feasibility Study

Given the lunar missions listed in Table IV for the 2016-2025 era, we see the emergence of sample return, human habitat survey, CubeSats/SmallSats, and, of course, high-resolution global mapping missions. It is fair to conclude this is a very crucial period for the various agencies (including KARI and NASA), as international lunar campaigns during the 2026-2035 decade, whether loosely federated or systemically coordinated, will demand some new capabilities be developed by the participating agencies, hence the advancement in lunar communication architecture. Table 6 summarizes some architecture attributes of the future space communications architecture.

Table 6. Lunar Space Communications Architecture Attributes – Progression Into A New Decade

Architecture Attributes	Current – 2025 era	2026 – 2035 era
Connectivity & topology	Largely point-to-point, some limited relay.	A mix of point-to-point and network-layer connectivity.
Data rates	Return data: Maximum ~ 125 Mbps. Forward data: Maximum ~ 4 Kbps.	Return data: Maximum ~ 300 Mbps. Forward data: Maximum ~ 250 Kbps.
Multiplicity of space data link protocols	By directionality & user regimes - CCSDS TC/TM/AOS and Proximity-1 protocols.	Unified Space Link Protocol (USLP); a single protocol across the entire international "network" of communication assets.
Service levels	Space communications services at data link layer and below; radiometric observables over Moon-Earth link.	Data link-, network-, transport-, and file-layer services; end-to-end service involving multi-nodes; radiometric observables over Moon-Earth link and proximity link. On-board autonomous position determination.
Service management	Agency-specific and/or asset-specific approaches for service requests, planning & scheduling, and asset monitor & control.	Internationally standard service management for service requests, planning & scheduling, & monitor & control, at both assets & network levels.

In Section V, we discuss a set of new capabilities to be developed during the 2016-2025 timeframe by the participating space agencies for infusion into the lunar space communications architecture.

A. Lunar Relay Network

This section describes our effort of searching the lunar relay constellation and assessing its coverage performance. The Moon, as Earth's satellite, is unique in the following ways:

1) Due to tidal locking, the Moon rotates at the same rate as its revolution of 27.3 days. Thus surface elements on the nearside always have direct line-of-sight with Earth, whereas those on the far side are permanently shielded, and those in polar regions have intermittent coverage. The landing assets on the far side would have to rely on a relay orbiter to communicate with Earth.
2) Due to the proximity of the Moon with Earth, Earth's ground stations can cover the nearside of the lunar surface.

We originally attempted to find lunar relay orbits whose coverage would bias towards the far side of the moon, but the slow rotating rate of the Moon proves to be a formidable challenge. The orbits we found are either unrealizable, too unstable, or too far from the lunar surface to be useful. We then considered relay network constellations that provide global coverage of the Moon using a combination of circular orbits and elliptical orbits. We performed a systematic search using the following criteria on the candidate constellations:

1) Orbits should be stable to minimize delta-V required for station keeping.
2) Range between an orbiter and a lunar surface element should be small to minimize space loss in communications.
3) Provide high average contact duration across all latitudes.
4) Support high percentage of contact time across all latitudes.
5) Minimize maximum gap time across all latitudes.
6) Include no more than three orbiters to contain cost.
7) Allow a viable evolution path to support upcoming lunar mission concepts.

This results in a constellation of 3 orbiters - one in a 12-hour circular elliptical orbit around the equator, and two in the 12-hour frozen elliptical orbits with their lines of apsides liberating over the North Pole and South Pole respectively[4,5]. The Keplerian elements of the three orbits are summarized in Table 7. The orientations and trajectories of the lunar relay constellation are illustrated in Figure 4. This constellation is scalable – launching one relay to meet initial needs and adding relays as number of missions increase.

Table 7. Summary of Keplerian Elements of the Lunar Orbits

Lunar Satellite Orbits	Semi-major Axis (km)	Eccentricity	Inclination (°)	Ascending Node (°)	Argument of Perilune (°)	True Anomaly (°)
12-hr circular equatorial	6142.4	0	0	0	315	adjustable[5]
12-hr elliptical North	6142.4	.599999	57.7	270	270	adjustable
12-hr elliptical South	6142.4	.599999	57.7	0	90	adjustable

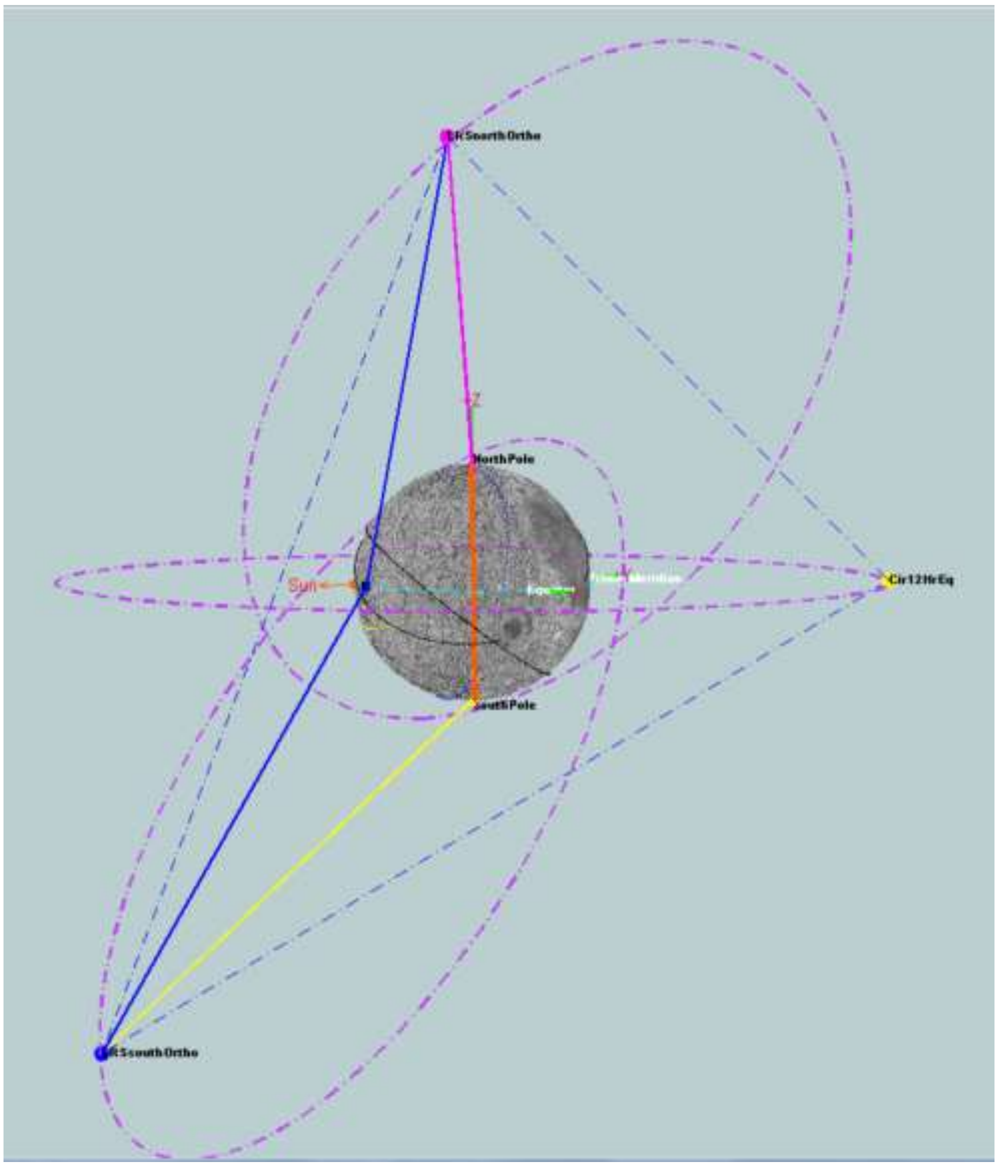


Figure 4. Lunar Relay Constellation

We performed detailed delta-V analysis for orbit station keeping by propagating the trajectories and taking into account the deterministic gravitational effects of Earth, Moon, and Sun, and the non-deterministic effect of solar pressure.

[5] One can adjust the orbit phasing (true anomaly) to provide impromptu coverage of lunar assets at reasonable Delta-V cost.

The maximum range for a lunar surface element to communicate with an orbiter in the circular orbit is 5892 km, and 9672 km with an orbiter in the elliptical orbit.

The average contact time duration, the total contact time per day, and the maximum gap time as a function of latitude are given in Figures 5, 6, and 7, respectively.

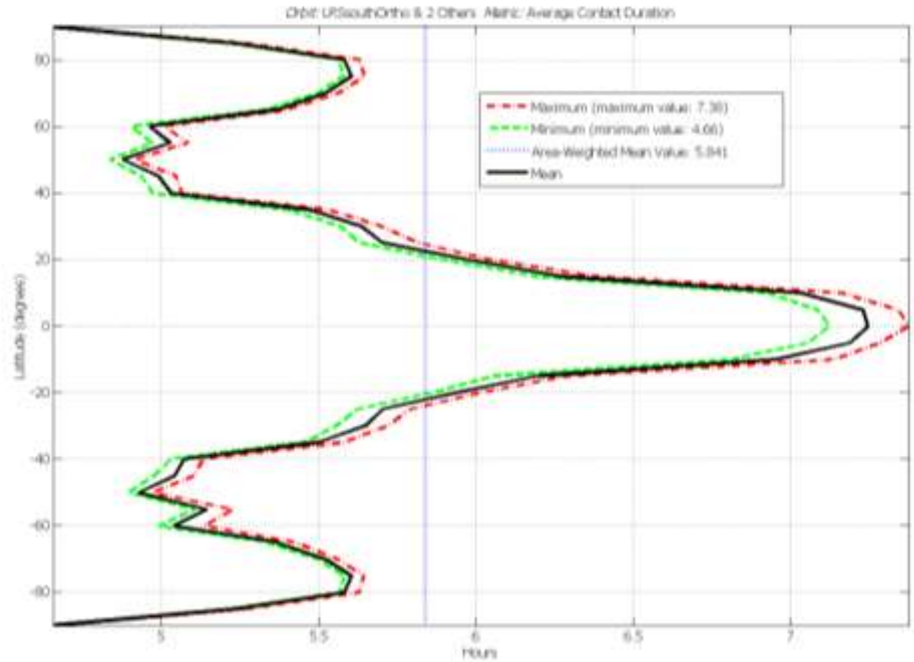


Figure 5. Average Contact Time Duration

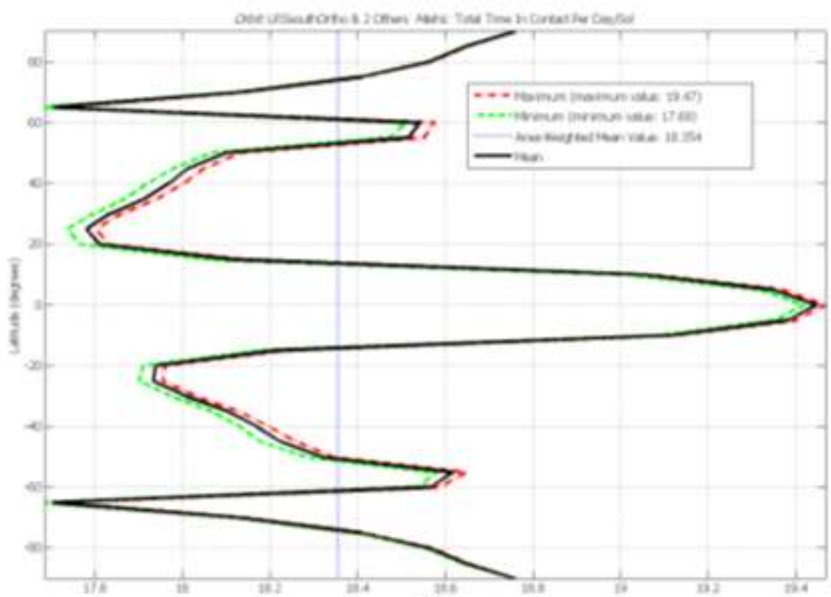


Figure 6. Total Contact Time Per Day (hours)

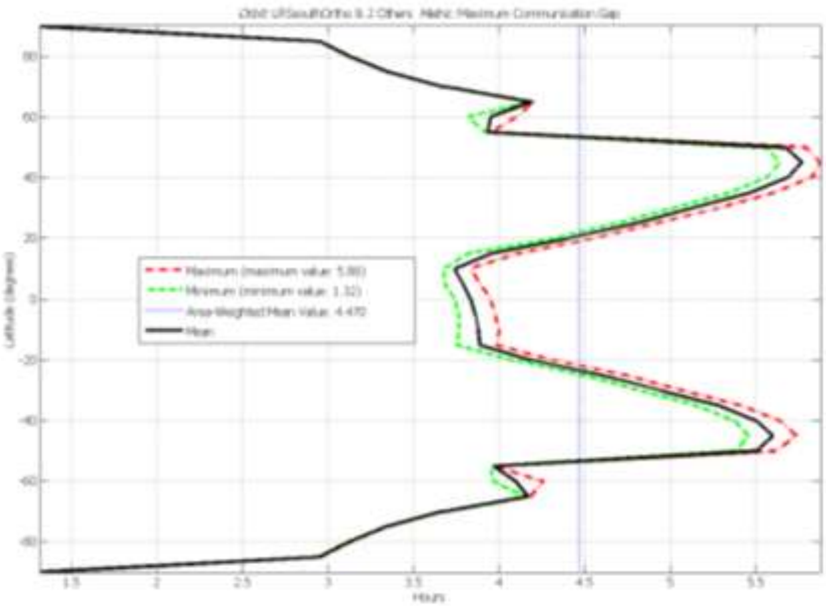


Figure 7. Maximum Gap Time

B. Lunar Relay Proximity Link

This section addresses the link analyses between the lunar relay orbiters and lunar surface elements for the 2015-2025 era. The KARI-NASA Study discusses using S-, X-, and UHF-band links to support the relay users. In this paper we only illustrate the UHF-band relay link analysis between the relay orbiter and a lunar mission user, using the concatenated code with a link margin of 3 dB. We summarize the orbiter's link parameters in Table 8[6], and a representative set of link parameters for the lunar surface vehicle in Table 9[7].

Table 8. KPLO Link Parameters and Link Margin Policy

Orbiter Transmitter Power (dBm)	Orbiter Antenna Gain (dBi)	Orbiter Circuit Loss (dB)	Orbiter Noise Figure (dB)	Orbiter Axial Ratio
37.48	4.8	-4.05	3.89	1.5

Table 9. Link Parameters of a Lunar Surface Vehicle

Lander Transmitter Power (dBm)	Lander Antenna Gain (dBi)	Lander Circuit Loss (dB)	Lander Noise Figure (dB)	Lander Axial Ratio
39	0	-1.7	1.4	1

We performed link analyses to determine the ranges of supportable forward link and return link data rates based on the maximum distances between the user spacecraft and the orbiters. The forward link data rate ranges from 14 Kbps to 700 Kbps, and the return link data rate ranges from 4 Kbps to 200 Kbps.

C. Ka-Band Behaviors for the Lunar Orbiter Direct-to-Earth Links

We considered the use of Ka-band for a lunar orbiter's direct-to-Earth (DTE) links, either with the DSN's 34-m Beam Waveguide (BWG) antenna at Madrid, or with KARI's planned 26-m BWG antenna located near Daejeon, South Korea. The orbiter's Ka-band link parameters are summarized in Table 10.

On the ground receiving side, weather effects dominate Ka-band link performance, both in terms of atmospheric attenuation and noise temperature increase. For the orbiter's downlink to the DSN's 34-m BWG antenna, we employed the antenna's link parameters and the weather loss model as published in the DSN Telecommunications Link Design Handbook 810-005[11].. For the link with KARI's 26-m BWG antenna, we scaled the KDSN 26-m

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[6] Based on Mars Reconnaissance Orbiter's UHF-band orbiter communication system.

[7] Based on Mars Science Lab's UHF-band rover communication system.

antenna Ka-band antenna Gain-to-Noise Temperature (G/T) performance with respect to that of a DSN 34-m antenna, and used the International Telecommunication Union (ITU) Ka-band weather loss model. We assumed a 20° elevation angle, 90% weather availability, and 3 dB link margin in this analysis.

Table 10. Orbiter's Ka-Band Link Parameters

Orbiter Transmitter Power (dBm)	Orbiter Antenna Gain (dBi)	Orbiter Circuit Loss (dB)	Orbiter Axial Ratio	Orbiter Pointing Loss
30	41	-0.5	0.63	-0.98

The above link analysis shows the orbiter's Ka-band supportable data rate ranges from 160 Mbps to 2200 Mbps with the DSN 34-m BWG antenna, and from 30 Mbps to 500 Mbps with the KARI's 26-m antenna. Based on the above data rate ranges and a maximum data rate of 400 Mbps, we assumed the set of discrete data rates supportable by the lunar relay orbiter to be: 10, 40, 70, 100, 130, 160, 190, 220, 250, 280, 310, 340, 370, and 400 Mbps.

Compared to S-band and X-band links, Ka-band is more sensitive to various fast- and slow-fading weather effects. As a result, a Ka-band pass is typically characterized with time-varying and unpredictable SNR. Also a Ka-band pass exhibits a larger difference between the lowest and highest supportable data rate than that of a S- or X-band pass. The standard space communication operations approach of sending the data once only, and/or of using one data rate per pass would result in a link margin that is larger than necessary most of the time within a pass. This renders the link relatively ineffective, and erodes the advantage of migrating to Ka-band. We demonstrated that by using a combination of ARQ retransmission protocol and multiple data rate per pass strategy, one could improve data return by a factor of two or more[1]. This is illustrated in Figure 8 that shows the Ka-band supportable data rate profile of a 10-hour pass with the 26-m antenna. The data volume returned using the best single data rate per pass is 8.7 Tb, compared to 12.5 Tb when multiple data rate changes per pass are used. The ARQ retransmission protocol is expected to achieve an additional 2 dB advantage[2] by lowering the operational SNR, thus increasing the data return to 20.1 Tb.

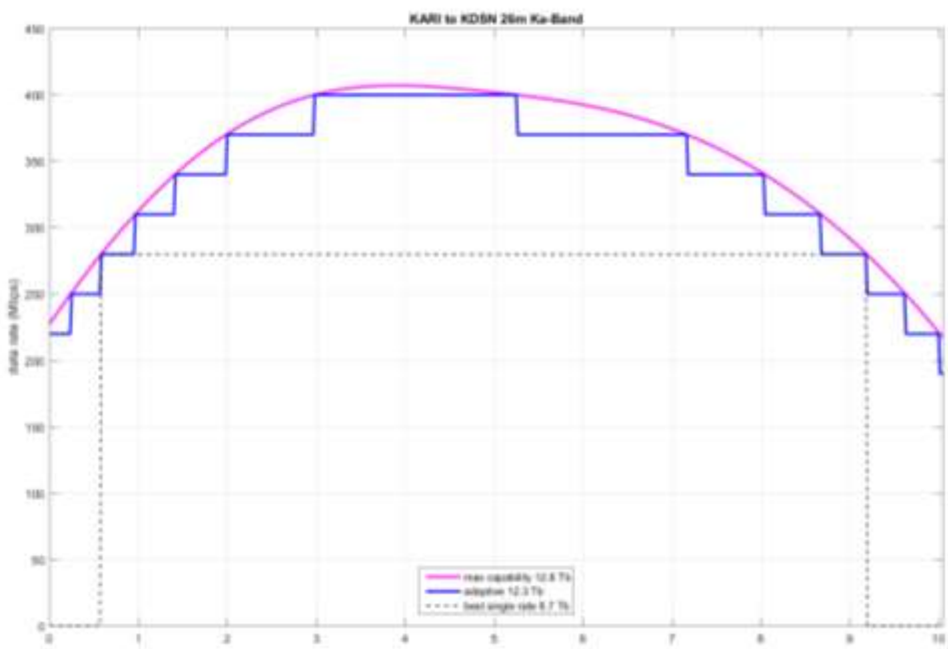

Figure 8. Ka-band Data Rate Profile and Multiple Data Rate Per Pass

D. Optical Link Behavior for the Lunar Orbiter Direct-to-Earth Links

For optical link, we baselined the flight and ground optical communication systems used on the Lunar Laser Communication Demonstration (LLCD) technology demonstration conducted in 2013[3]. Table 11 summarizes the LLCD system characteristics.

Table 11. LLCD System Parameters

LLCD System Parameters	Values
Spacecraft Laser Transmitter Power (Watts)	0.5
Spacecraft Optical Aperture (cm)	10
Spacecraft Transmitting Modulation	16 PPM (Pulse Position Modulation)
Ground Station Receiving Telescope	4x40 cm (~80 cm equivalent aperture)
Ground Station Photon Detector	Nanowire detector
Operational Constraints	Elevation > 20°,Spacecraft-Earth-Probe (SEP) angle > 5°
Transmit Laser Wavelength (nm)	1550
Spacecraft Pointing Error (μrad)	2.6
Spacecraft Optical Loss (dB)	3.9
Ground Station Telescope Focal Length (m)	10
Ground Station Telescope Optical Loss (dB)	5.4
Ground station Telescope Cleanliness Level	1000
Clear Sky Atmospheric Channel/Turbulence Loss	0.1 dB
Nanowire Detector Efficiency (%)	80
Nanowire Detector Jitter (ns)	20
Downlink Code	Rate ½ SCPPM

For the lunar relay scenario, the supportable data rate ranges between 41 Mbps and 46 Mbps. The supportable data rate of a 6-hour pass is shown in Figure 9.

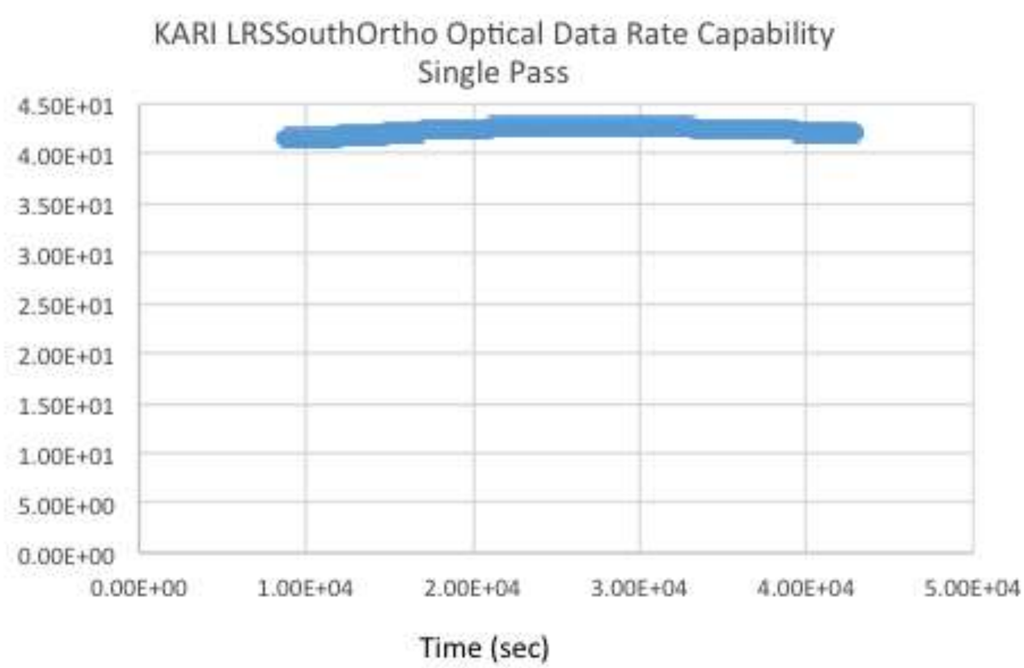

Figure 9. Optical Link Data Rate Pass Profile

We have the following interesting observations:

1) The supportable data rate profile of an optical link pass is relatively flat, compared to that of the Ka-band. Thus, there is not much advantage in using multiple data rates per pass to optimize data return.
2) Like the Ka-band link, the optical link is sensitive to atmospheric turbulences and other weather effects. Thus, operational strategies like interleaving and Automatic Retransmission Request (ARQ) would help to increase data return and to ensure reliable communications.

E. Space Internetworking per Disruption Tolerant Network (DTN)

An increasing number of deep space missions nowadays question whether traditional space communications will be challenged to overcome the multitude of problems due to low SNR, intermittent connectivity, and long haul delay. The hottest news and achievements of space science and research in recent years may be exploration by NASA's MSL rover (2012), Curiosity (2013), CNSA Chang'e 3's exploration (2013) of Moon, ESA Rosetta's exploration (2014) of Comet 67P/Churyumov-Gerasimenko, and NASA New Horizons' exploration (2015) of Pluto, which are very astonishing achievement since such a deep space journey was possible with current technology. In contrast to the wonderful evolution of cruise and navigation technologies in deep space, there are no remarkable changes in deep space data communications. Communication subsystem designs remain conservative in technology and performance analysis. Therefore even a state of the art deep space mission has to endure extremely slow communication data rates during data transmission from and to ground stations. For example the downlink speed of ESA's Rosetta was 22 kbps and for NASA's New Horizons, the data rate was limited to 1 kbps when it flew past Pluto.

The DTN protocol is an emerging paradigm as one of possible solutions to cope with these constraints. If internetworked space resources such as multiple relay orbiters on the Moon existed along the path between source and destination nodes, the space link could be maintained between lunar surface rover/lander and Earth ground stations even under intermittent connections. DTN internetworking uses a store-and-forward mechanism to deal with intermittent connection. When a node fails to transfer bundles to the next node on the path, the node holds the data until the connection is re-established and tries until it succeeds and transfers custody to the next node. The TCP/IP protocol used so highly in terrestrial networking drops data when transmission fails requiring higher layer processing (e.g., application layer) with greater delay/latency to achieve the same transfer of data. Actual conditions of deep space communication may be summarized as following[6]:

1) Greater signal propagation latencies up to seconds, minutes, even hours
2) Low data rates, 8-256 kb/s
3) Intermittent scheduled connectivity
4) Asymmetric data rate (bandwidth) for forward link (faster in general) and return link (slower in general)

Those conditions make it hard to use ground TCP/IP congestion control in deep space communication environment.

DTN provides some advantages on deep space communication as followings:

1) Common protocol stack in multiple spacecraft from multiple manufactures for anticipating deep space congestion control
2) Flexible and higher data rate design between relay nodes and end node
3) General relay service capability as commercial

NASA has DTN experimental network (DEN) at Space Communication and Network (SCaN) division and the implementation and utilization of DTN on International Space Station (ISS)[7] have been discussed between space agencies. As a result, international cooperation for implementing DTN protocol has been done by NASA-ESA (2012) and NASA-JAXA (2013)[8] And NASA-KARI/Electronics and Telecommunications Research Institute (ETRI) will be entering a joint test for the latest version of Interplanetary Overlay Network (ION) (see http://sourceforge.net/projects/ion-dtn/) for the purpose of assessing the performance of DTN protocol on ground environment, targeted to completion in 2018. The purpose of the DTN experiment between NASA-KARI/ETRI is to promote the international adoption of DTN and, through the joint test (online) for the latest ION release conducted between NASA's DEN and KAR/ETRI's experimental DTN nodes, to evolve the ION software.

KARI has started developing of Korea Pathfinder Lunar Orbiter (or KPLO) since 2016, and the Space Internet payload which hosts DTN algorithm for technical demonstration purpose will be developed by ETRI. Those test results from the DTN experiment test between NASA and KARI/ETRI will be taken into consideration during the development of the Space Internet payload for KPLO.

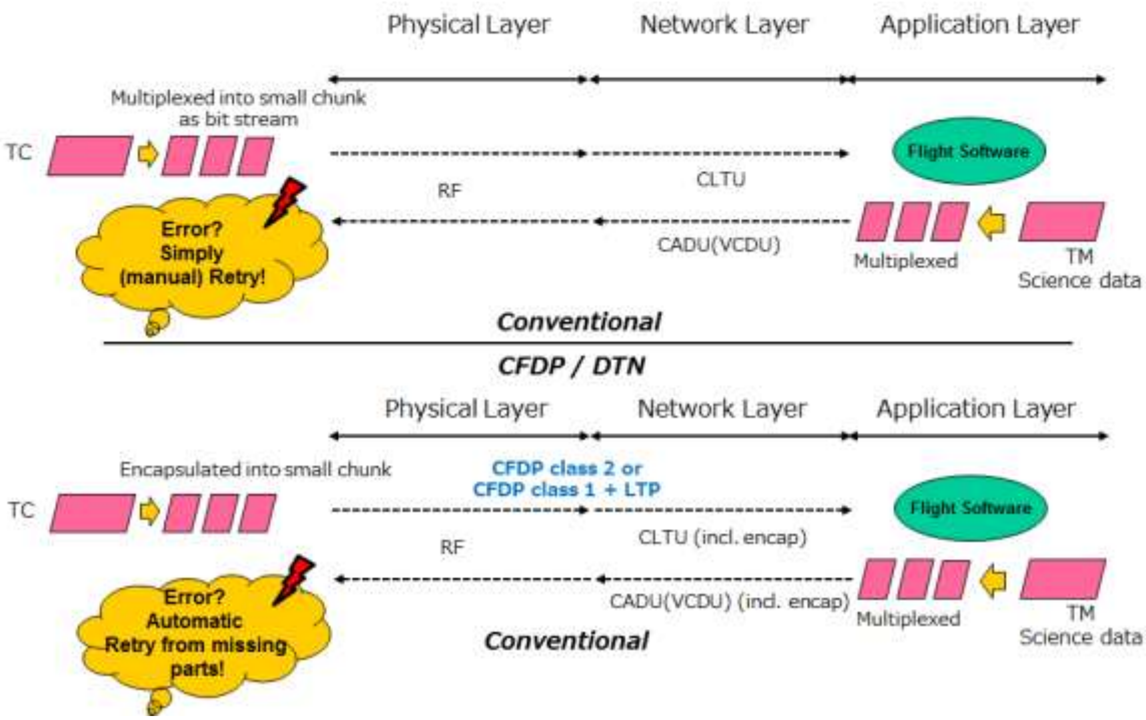

Figure 10. **Differences Between Conventional and CFDP/DTN Communications Approaches.**

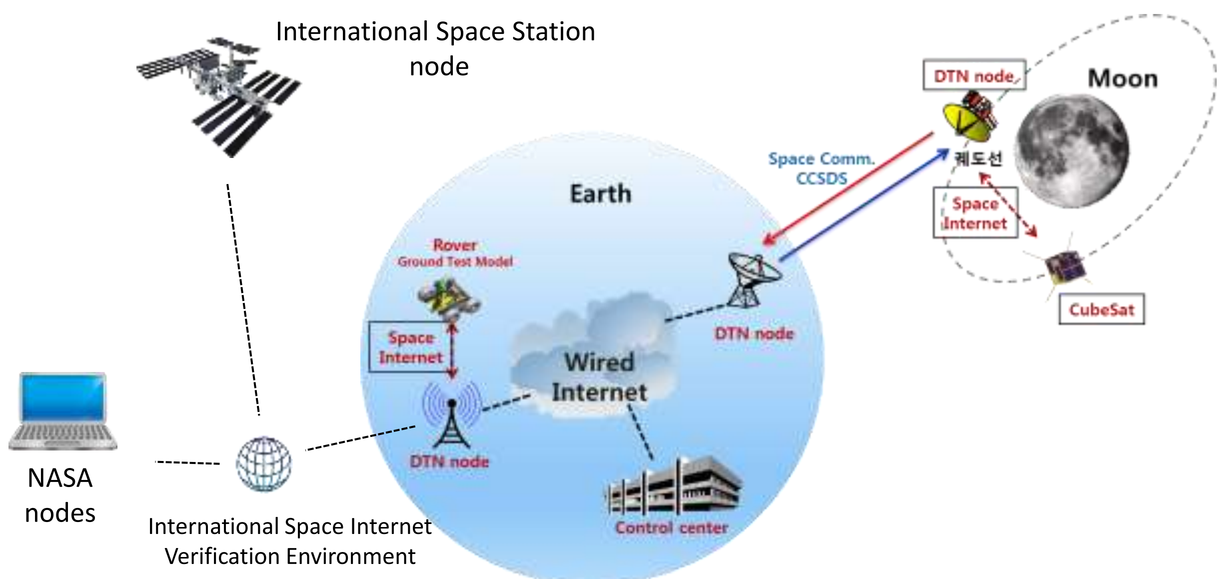

Figure 11. **Space Internetworking over DTN – The KPLO DTN Experiment Architecture**

F. Space Data Link Protocol

At data link layer, at present there are multiple CCSDS protocols used by the space missions, i.e., Telecommand (TC), Telemetry (TM), Proximity-1, and Advanced Orbital Systems (AOS). Over the past two decades, improvements and enhancements of each protocol were conducted independent of the others. However, major deficiencies persisted: 1) transfer frame size and accountability is too limited for CCSDS agencies envisioned future mission set. This is largely due to advances in forward error correction coding algorithms and advances in microelectronic technology allowing improved uplink and crosslink performance to be achieved for space borne systems; 2) there are inadequate spacecraft ID assignments available in the current CCSDS link layer protocols; 3) for future missions that must communicate over multiple types of space link, i.e., forward, return, proximity, and high-rate links, the multiplicity of data link protocols is problematic in terms of implementation and operational costs.

As such, in anticipating the needs of upcoming missions, as exemplified by the diverse lunar missions, convergence of CCSDS protocols into a single protocol becomes more pressing than ever before. The Unified Space Link Protocol (USLP) currently designed by the CCSDS will meet the requirements of space missions for efficient transfer of space application data of various types and characteristics over space-to-ground or space-to-space communications links.

Table 12 gives a summary on the features and benefits of the USLP. Table 13 contains a comparison between the USLP and an existing space link protocol, i.e., AOS.

Table 12. Features and Benefits of Unified Space Link Protocol

USLP Features	Benefits
Provides a single link protocol used by flight and ground across all manned and robotic space links	• Applicable to large and diverse set of missions from ISS to Cubesats; • Once implemented, reduces future development & testing from 4 to 1 protocol.
Decouples the link framing from the channel coding	• Using software defined radios, missions may choose to swap in higher performing codes (~3 to 8 dB gain) during development or flight operations. • Resulting in trade off between using less power (lower output power, smaller antenna or reduced pointing constraints) or opting for higher data rates.
Expands the number of Spacecraft CCSDS must identify	• Existing name space is 75% full. • Expectation is current ID space will run out in the next 5-10 years due to small sat growth and slow attrition.
Allows *direct* data delivery of other protocol data units (PDUs)	• Currently, CCSDS Space/Encapsulation Packet required to contain other PDUs • USLP is more efficient using direct insertion requiring no encapsulation of IP Datagrams or DTN bundles

Table 13. A Comparison of USLP to AOS

Structural Attributes	AOS	USLP
Maximum Frame Size (in Octets)	2048	65536
Frame Size constraint	Managed/Fixed	Variable/Signaled
VC-OCF Presence in VC	Managed	Signaled
Insert Zone Presence	Managed	Signaled
Insert Zone Size	Fixed	Signaled
Frame Error Control Field	Fixed	Signaled
Frame and Code block Alignment	Fixed	Fixed/Variable
Spacecraft IDs	256	8192
Sequence Counter Size	Fixed (2.7e^{8})	Variable (0-7e^{16})
Virtual Channels	64 maximum	64 or 32 independent/32 dependent

G. Forward Space Link – Forward Frame Service

The forward data services presently offered by the ground stations of the space agencies for cross support are primarily based on the Forward CLTU Service (for the service provider-service user interface) and the TC at the space data link (for the point-to-point ground station-to-spacecraft interface). As the lunar space communications progresses into the era of space internetworking, as described in E of Section V, the network layer functionality will demand the ground stations to multiplex streams of frames from multiple sources, i.e., DTN nodes and non-DTN nodes, into a single physical link for radiation of forward data to the destined user spacecraft. Such a multiplexing mechanism allows multiple sources of a user mission to asynchronously transmit their individual forward data streams to the respective destination entities on the spacecraft, during the same uplink session. Arguably, for some operational scenarios, this leads to more efficient utilization of the uplink. Moreover, to ensure that a ground station along with its spacecraft counterpart is fully, truly accountable for its performance at space data link layer, the ground station must perform coding and synchronization for the forward data received the user mission. That also means the function of filler frames (or bits) insertion to maintain a robust, synchronous physical link, when there is no information bits to be modulated on the link, must be done by the ground station.

The forward frame service, therefore, is for the service-providing ground stations to receive uncoded frames from sources of a user mission, encode the frames, multiplex the frame streams onto the single physical link while manage the uplink, either synchronous (AOS type) or asynchronous (TC type) link, by performing filler frames (or bits) insertion.

Figure 12 illustrates a use scenario associated with the forward frame service in the lunar space communication architecture of the future.

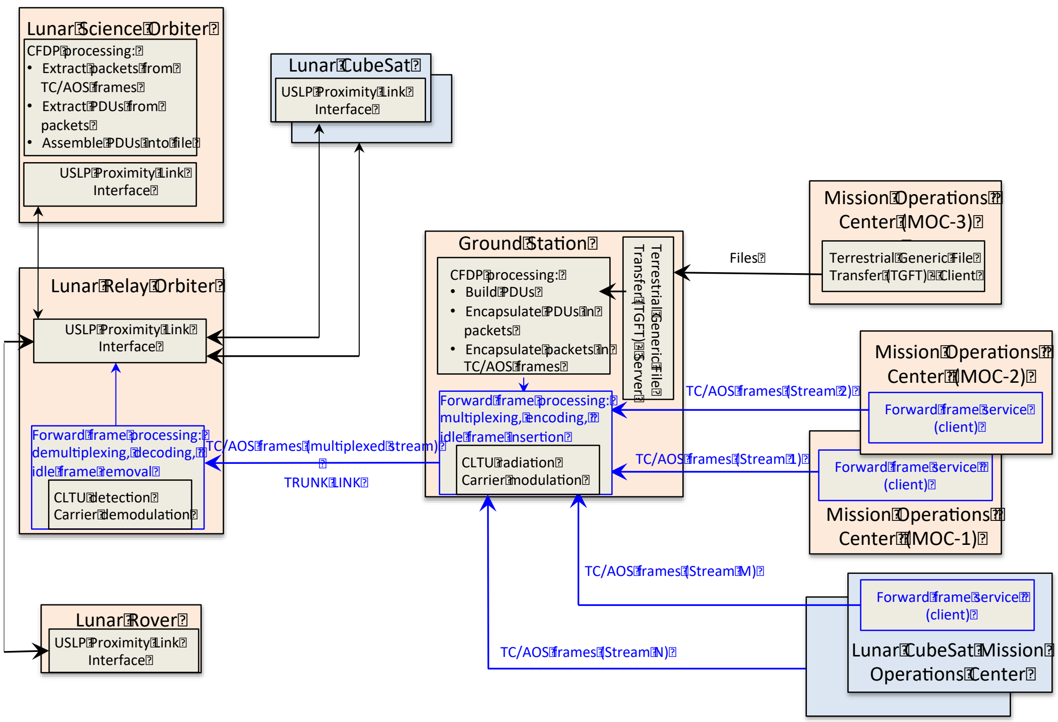

Figure 12. Forward Frame Service – A Lunar Use Scenario

H. File Services

File services are an emerging type of service in space communications. The communication assets provide forward file service by sending a file, received from the mission ground system, to the spacecraft over the space link. For the return file service, the communication assets receive a file from the spacecraft and transfer it to the mission ground system. Although for several decades the use of files as data units for the management and transfer of data has been a well-understood concept, commonly practiced in terrestrial systems, file transfer over the space link was a more recent development.

However, the advancement of embedded operating systems, e.g. VxWorks and RTEMS, that provide a file management system with a rich set of functionalities to support on-board memory and data management for RAM disk or flash device, has led to the need for file transfer over the space link. The advantages of the file service over the stream-oriented data transfer of the return frame or CLTU service are: (1) it ensures the data integrity of a file since the file is an accountable data unit; (2) it enables the automated operations for reliable data transfer.

During the joint KARI-NASA study, it was foreseen that file service would become a major function for lunar mission operations in near future given the rapid growth of on-board memory size and the increasing complexity of payloads as witnessed in the current space industry trend. The operations concept is based on the on-board file management capabilities that store file chunks in on-board storage devices and the CCSDS File Delivery Protocol (CFDP)[9] capability that processes file packets and collaborates with the sender/receiver for reliable transfer and delivery of files during transaction over space link. Moreover, in the 2016-2025 timeframe, for a higher degree of interoperability over the ground-to-ground link between a ground station and a mission operations center, the CCSDS Terrestrial Generic File Transfer (TGFT) protocol will be employed

NASA has operated file services (for return and/or forward data) in a few missions, e.g., MESSENGER, Deep Impact, LRO, and MRO. They are all based on a simple on-board file management system and the CFDP capability. ESA will utilize CFDP for its Euclid mission to be launched in 2020[10]. Going beyond that, NASA's Core Flight System (CFS) software, developed and maintained by NASA GSFC, offers a more powerful file management system that is reusable, reconfigurable, and platform-independent.

Figures 13 and 14 illustrate a use scenario for the forward and return file services in the lunar communications environment. While the scenario in these figures involves a lunar relay, the file services are also applicable to situations where there is no lunar relay in the middle.

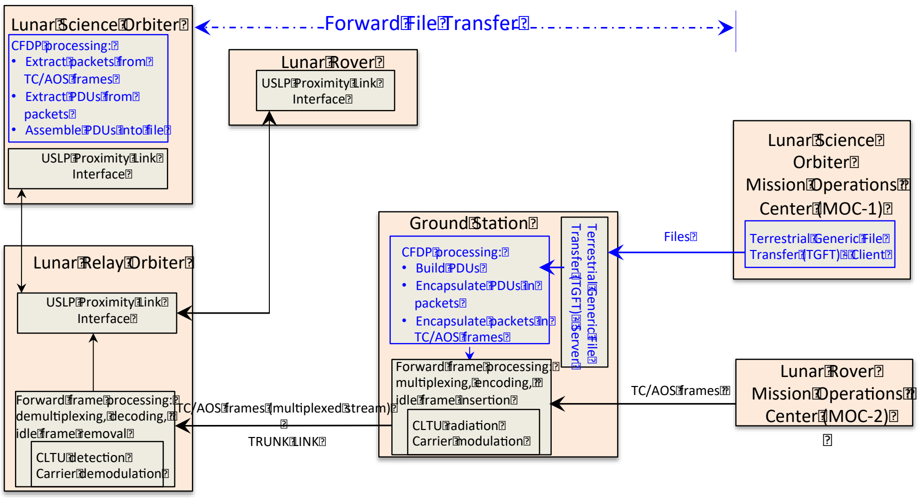

Figure 13. Forward File Service – A Lunar Use Scenario

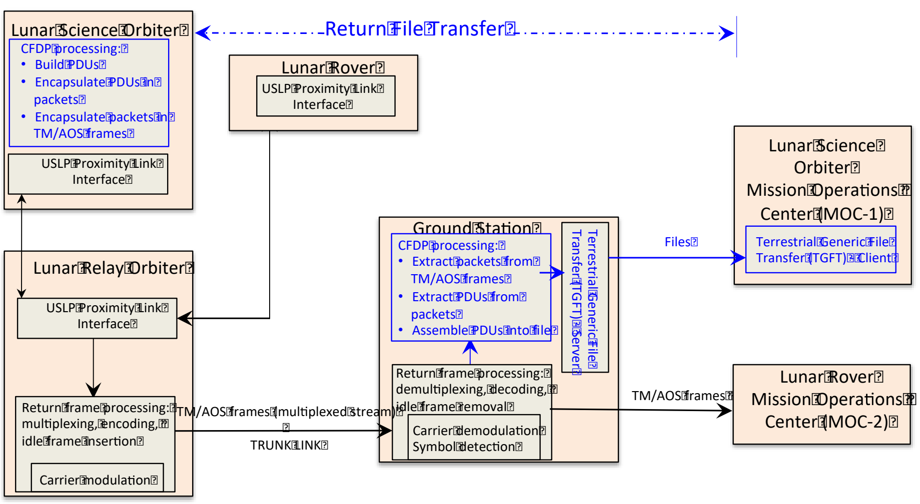

Figure 14. Return File Service – A Lunar Use Scenario

I. Cross Support Service Management

To achieve a new level of interoperability between communication assets of the various space agencies that are engaged in lunar exploration, the standardization of service management functions is crucial. At present, agency-specific and network-specific approaches are used in planning and scheduling of space communications support largely because of the lack of CCSDS service management standards. By 2020, it is envisioned that a full suite of service management standards will be available for infusion by communications service-providing organizations. The ramifications to the international lunar exploration will be very significant. Table 14 summarizes a set of standard service management interfaces and the relevant functions, as shown in Figure 3, they support.

Table 14. A List of Standard Service Management Interfaces

Service Management Interfaces	Functions in Figure 3 Supported
Service Catalog	Service Planning
Service Agreement	Service Planning
Service Configuration Profiles	Service Request Scheduling, Network Configuration & Control
Planning Data	Service Planning, Service Request Scheduling, Network Configuration & Control
Space Link Event Sequence	Network Scheduling, Network Configuration & Control
Service package	Network Scheduling, Network Configuration & Control
Schedule of Services	Service Request Scheduling
Service Accounting	Service Accountability Reporting
Service Execution Control	Network Configuration & Control
Monitor Data	Network Monitoring

Conclusions & Summary

Through the joint KARI-NASA study, a space communications architecture, which serves as a framework for cross support to the KPLO mission via the communications and navigation capabilities provided by NASA's DSN and the Korea DSN (KDSN), was defined. The architecture has some powerful features that will be operational for supporting the KPLO plus a hypothetical lunar relay capability. This architecture can be viewed as a representative architecture for lunar communications during the 2016-2025 timeframe.

Going beyond that, in anticipating the international lunar explorations during the decade of 2026-2035, it is concluded that the 2016-2025 timeframe is a crucial period for the international space agencies to advance the lunar space communications architecture. We have defined an architecture that features a lunar relay satellite constellation, the lunar network, the high-rate links for both Moon-Earth and proximity communications, a new service paradigm, and a set of advanced communication protocols.

Acknowledgments

The authors thank the management of the KARI Lunar Exploration Program and NASA Space Communications and Navigation (SCaN) Program for their support to the KARI-NASA joint feasibility study during October 2014 – April 2015 period. Their strong advocacy in furthering the international collaboration for space exploration is greatly appreciated. Part of the work on the NASA side was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the NASA.

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